cellular phone infrastructure and consumer devices that incorporate location services, digital imagers, accelerometers, Bluetooth access to off-board sensors, and easy programmability. These systems can be leveraged by individuals and communities to address a range of civic concerns, from safety and sustainability to personal and public health. At the same time, they will push even further on our societies' concepts of privacy and private space.

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The Impact of Sense and Respond Systems

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Sense and respond (S&R) systems based on information technology amplify one of the most fundamental characteristics of life — the ability to detect and respond to events. Living things thrive when they respond effectively to what's going on in their environments. A zebra that doesn't run away from a hungry lion dies and one that runs away unnecessarily wears out. Organizations sense and respond collectively: lions in a pride signal each other when they hunt; societies deal with crises by harnessing capabilities of governments, charities, and individuals. When our ancestors hunted millennia ago, they saw as far as the eye could see and threw spears as far as their muscles let them. Today, S&R systems let us detect events far out in space and respond anywhere on the globe. By 2020, S&R systems will become an integral part of the activities of people and organizations around the world whether they're rich or poor, in farming or medicine, at work or at play.

Mammals sense and respond by using the complementary functions of the sympathetic and parasympathetic nervous systems. The sympathetic nervous system manages "fight or flight" responses while the parasympathetic nervous system handles ongoing functions such as digestion. By 2020, individuals and companies will routinely use S&R systems to amplify their sympathetic and parasympathetic nervous systems: they'll use them to improve the efficiency of day-to-day operational activities and also to respond to rare, but critical, threats and opportunities.

S&R systems have different characteristics than traditional information technology services:

- S&R systems interact with the environment. Computation and communication are relevant only insofar as they support interaction.
- S&R systems direct the activities of components such as sensors, computation engines, data stores, and responders. The programming metaphor for S&R systems is agent choreography rather than the sequential flowchart of a cooking recipe.
- People configure S&R systems to operate over a longer term than conventional service invocations. The invocation of a service — such as a Web search for documents dealing with the keyword "Internet" — handles an immediate, and possibly transient, concern. By contrast, a request to receive alerts about new documents with the keyword "Internet" asks for a longer-term interaction; the request remains in place until the requester deletes it.
- S&R systems are predictive and proactive: they predict what organizations and individuals will need to do, and they carry out activities that users might need in the future. The results of these proactive activities are discarded if the user doesn't need them. A simple example of such a proactive system is one that determines your best commutes to both the office and the airport; if you go to the office, then the work in determin-

ing the optimum commute to the airport is wasted. The decreasing costs of computation and communication compared to the costs of other goods and services will result in more proactive applications.

Feedback control has been widely used since James Watts' centrifugal governor in the 18th century. Militaries have had command and control systems based on information technology since World War II. Market makers in stocks employ complex algorithms that respond to events in milliseconds. Businesses have used intelligence algorithms for more than 25 years. All these technologies are examples of S&R systems. So, what's new about 2020?

S&R technologies will become commonplace in 2020. What was once the exclusive province of sophisticated engineering companies, military contractors, and financial firms will be used by everybody: teenagers, homemakers, senior citizens, CIOs, CFOs, and CEOs. They'll use S&R technologies in 2020 as naturally as they use search engines today.

What forces will make S&R commonplace in 2020?

- Advertising revenues will drive dot-com companies to offer services that allow consumers to create personal S&R systems, including activity-specific dashboards that integrate calendar, mail, Web searches, news alerts, stock feeds, and weather forecasts for aspects ranging from bicycling to investing. Nothing provides more information about you than what you want to sense and how you want to respond, and advertising companies will offer services to gain that data and target "markets of one."
- Decreasing sensor and responder costs and form-factors will drive penetration of S&R systems. Accelerometers that cost hundreds of dollars will cost a tenth as much when they become commodity components of mobile phones and laptops. A rich variety of sensors, such as heart monitors, will be coupled to mobile phones. GPS devices will drive location-based S&R services.
- Programmers will be able to easily structure S&R applications to exploit clusters of machines and multicore computers.
- Advances in several areas of information technology will simplify implementations of S&R systems. These areas include information extraction from natural language text, images, and videos; business intelligence, analytics, machine learning, and optimization; notations and user interfaces for specifying S&R systems; and personal devices such as smart phones and smart clothing.

S&R systems will support all aspects of daily living: water, food, health, energy, security, housing, transportation, and research. Green energy resources such as wind and solar power are dynamic; so, systems that harness these resources must sense their availability and respond appropriately. Indeed, the smart grid can't exist without S&R technologies. Concern about food safety will lead to national farm identification systems that track every farm animal with an RFID tag or microchip. By 2020, many countries will require electronic pedigree systems that record major events — such as shipment and prior sales of pharmaceutical drugs. S&R technologies will play central roles in science projects such as the Large Hadron Collider, and they'll play an even larger role in national defense.

Community-based S&R systems will empower hundreds of thousands of ordinary people equipped with sensors and responders in their mobile phones, cars, and homes to help their communities. People in earthquake zones such as Lima, Jakarta, and Los Angeles will use inexpensive personal accelerometers to send information about ground movement to S&R systems that determine epicenters and provide short (seconds) of warning of intensive shaking. Community-based measurements of wind speed, temperature, and humidity will provide firefighters with microscale data when fighting forest fires in Greece, California, and Australia. Ordinary people will use sensors and the Internet to collaborate on citizen-science projects — for instance, amateur and professional astronomers across the globe working together to record transient astronomical events.

The widespread use of S&R has some dangerous consequences and faces several hurdles:

- An insidious consequence of a badly designed S&R system is that it can dissipate one of the truly scarce resources of this century: attention. Well-designed S&R systems amplify attention, whereas poorly designed

systems dissipate it by interrupting us and giving us opportunities to get sidetracked.
- Concerns about privacy are a barrier. An S&R application will make individuals and organizations more effective; however, the company that hosts the application will know the most important aspect of its users — their goals.
- Security is a major hurdle. Widespread use of sensors and responders gives hackers multiple points of entry into S&R systems. The systems that form the backbone of critical services such as food, water, energy, and finance are likely to have common components; successful attacks or errors in these components will have devastating consequences.
- S&R systems enable efficient use of limited infrastructure, such as electric grids and roads, by distributing demand over time and reducing peak congestion. As a consequence, the infrastructure operates close to capacity much of the time, and an increase in demand can take it over the edge and bring the system down. Resilience requires some spare capacity as well as S&R technology.

Society will feel the impact of S&R technologies in many ways. S&R systems will let people conduct a variety of new services from anywhere. They'll let nurses in Manila monitor senior citizens in Manhattan, and engineers in Bangalore monitor intrusion into buildings and networks in London. S&R technologies will accentuate the digital divide; those who master the technology will function better at school and work than those who don't.

The next 10 years will see rapid development of S&R technologies in applications that touch the daily lives of people across the globe.

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The Play's the Thing

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For most of the 20th century, our entertainment media — film, music, novels, and TV — were happily non-interactive. But a significant shift in the past 30 years toward interactive entertainment has built the computer game industry into a powerhouse that generates more than US$19 billion in annual revenue worldwide, rivaling both music sales and box office receipts. For most of this industry's history, games were primarily designed to be played alone, but even this has changed, with the single-player focus shifting in the past five years to exploit the increase in broadband availability and include additional players.

As computer and console games continue to exploit new services available via the Internet, the design of gameplay itself will correspondingly change. These changes will expand the already powerful social and cultural roles that games play as well as enable the development of new core game technologies involving 3D graphics, real-world/augmented reality interfaces, and artificial intelligence.

Playing in the Cloud(s)

From a market perspective, it's the players' desire for social connectivity that will drive the coming shift to networked gameplay. Already, developers of major game titles are marginalizing their single-player modes and focusing their development efforts on enhancing their networked multiplayer offerings. In fact, some high-profile games are now designed exclusively for online play. Although the shift toward network-enabled games is currently motivated by the desire to enhance gameplay with a social element, the added computational power the shift brings has much broader significance.

We can categorize the kinds of innovations we'll see in game development as a result of the increased access to network services as belonging to one of two types: those that make current high-end game capabilities available across a range of hardware and those that bring new